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EMBEDDED ELECTRODE INTEGRATED OPTICAL DEVICES AND METHODS OF FABRICATION

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application Serial No. 60/428,160, filed November 21, 2002. This application is related to U.S. Patent Application Serial Nos.: 09/916,238 (BAT 0036 PA), filed July 26, 2001; 10/098,730 (BAT 0036 IA) and 10/098,731 (OPI 0001 PA), filed March 15, 2002; 10/302,793 (OPI 0003 PA), filed November 22, 2002; and 10/395, 835 (OPI 0005 PA), filed March 24, 2003, the disclosures of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

The present invention relates to optical signal transmission and, more specifically, to improved waveguide devices useful in applications requiring modulation, attenuation, polarization control, and switching of optical signals.

BRIEF SUMMARY OF THE INVENTION

Integrated optical devices including embedded electrodes and methods of fabrication of such devices are provided. In accordance with one embodiment of the present invention, a method of fabricating an integrated optical device is provided. The method comprises the acts of: (i) providing a support wafer defining an electrode support surface; (ii) forming an electrode pattern over the electrode support surface of the support wafer; (iii) forming a non-polymeric buffer layer on at least a portion of the electrode pattern and over at least a portion of the support wafer; (iv) forming a waveguide core material layer over the non-polymeric silica-based buffer layer; (v) removing portions of the core material layer to define a waveguide core; and (vi) positioning a cladding material in optical communication with the waveguide core such that the buffer layer, the cladding material, and the waveguide core define an optically-clad waveguide core.

In accordance with another embodiment of the present invention, the buffer layer is formed over the electrode pattern and the support wafer through a sol-gel process characterized by a maximum processing temperature below about 400°C.

In accordance with yet another embodiment of the present invention, an integrated optical device is provided comprising a support wafer, an electrode pattern, a non-polymeric silica-based buffer layer, a waveguide core material layer, and a cladding material. The support wafer defines an electrode support surface. The electrode pattern is formed over the electrode support surface of the support wafer. The non-polymeric silica-based buffer layer is formed on at least a portion of the electrode pattern and over at least a portion of the support wafer. The waveguide core material layer is formed over the buffer layer. The cladding material is in optical communication with the waveguide core such that the buffer layer, the cladding material, and the waveguide core define an optically-clad waveguide core.

Accordingly, it is an object of the present invention to provide improved waveguide devices and a scheme for fabricating improved waveguide devices useful in applications requiring modulation, attenuation, polarization control, and switching of optical signals. Other objects of the present invention will be apparent in light of the description of the invention embodied herein.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The following detailed description of specific embodiments of the present invention can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

Figs. 1-3 are schematic illustrations, taken in cross section, of embedded electrode integrated optical devices according to various embodiments of the present invention.

Fig. 4 is a schematic illustration, take in plan view, of portions of the integrated optical devices illustrated in Figs. 1-3.

Figs. 5-7 illustrate a method of fabricating integrated optical devices according to the present invention;

Figs. 8-12 are schematic illustrations, taken in cross section, of integrated optical devices according to various embodiments of the present invention including control electrodes in addition to the embedded electrodes illustrated in Figs 1-3;

Fig. 13 is an illustration of an alternative embedded electrode design according to the present invention; and

Figs. 14 and 15 are schematic illustrations, taken in cross section, of further integrated optical devices according to various embodiments of the present invention.

DETAILED DESCRIPTION

Referring initially to Figs. 1-4, integrated optical devices 10 according to the present invention are illustrated. It is noted that the devices 10 are illustrated in a somewhat generic nature because the devices 10 may take the form of any one of a variety of specific types of waveguide devices where embedded electrodes, an optically functional or non-functional cladding, and an optically functional or non-functional waveguide core are employed. For example, the teachings of the present invention may be employed in the context of one or more devices disclosed in the above-noted related patent applications, the disclosures of which have been incorporated herein by reference. The teachings of the present application may be utilized with the teachings of these and other pertinent references to render any one of variety of workable devices and fabrication schemes.

Referring again to Figs. 1-4, each integrated optical device 10 comprises a support wafer 20, an electrode pattern 30, a non-polymeric silica based buffer layer 40, a waveguide material layer 50 and core 52, a cladding material 60, and one or more contact regions 80. The support wafer 20 is provided as a silicon wafer 24 carrying a silica coating 25, the silica coating defining an electrode support surface 22. The electrode pattern 30 is formed over the electrode support surface 22 of the support wafer 20. The buffer layer 40 is formed over the electrode pattern 30 and the support wafer 20. The waveguide core material layer 50 is formed over the buffer layer 40.

For the purposes of describing and defining the present invention, it is noted that a distinction is intended between the respective meanings of the positional terms "over" and "on." Specifically, if a layer is formed "over" another layer it is contemplated that an intervening layer of another material may be present between the two layers. In contrast, if a layer is formed "on" another layer, no intervening layer is contemplated. For example, referring to Fig. 1, the core material layer 50 may be said to be formed "over," but not "on" the support wafer 20.

As will be described in further detail herein, the electrode pattern 30, the buffer layer 40, and the waveguide core 52 are formed such that the electrode pattern 30, which may include one or more electrically isolated, substantially co-planar control electrodes 32, 34, is embedded in the device beneath the waveguide core 52. One or more contact regions 80 are formed over the

electrode pattern 30. Conductive leads 82 may be brought into contact with the electrode pattern 30 in the contact regions 80 with the aid of a conductive epoxy 84, via wire bonding, or through any other suitable means for conductively coupling the leads 82 to the electrode pattern 30. Prior to bringing the conductive leads 82 into contact with the electrode pattern, the pair of contact regions may be treated with hydrofluoric acid or another suitable material to remove residual insulating material, including residual cladding material, from the pair of contact regions 80.

The various fabrication methods according to the present invention may be described with reference Figs. 5-7. Initially, the support wafer 20 defining the electrode support surface 22 is provided. The electrode pattern 30 is formed over the electrode support surface 22 of the support wafer 20 (see Fig. 5). Next, the non-polymeric, silica based buffer layer 40 is formed over the electrode pattern 30 and the support wafer 20. A waveguide core material layer 50 is formed over the buffer layer 40 (see Fig. 6). Portions of the core material layer 50 are removed to define a waveguide core 52 and a pair of cladding containment regions 54 extending along opposite sides of the waveguide core 52 in a direction substantially parallel to a longitudinal dimension of the waveguide core 52 (see Fig. 7). In this manner, the cladding material 60 illustrated in Figs. 1-3, which is often initially a substantially non-rigid material like a gel or a viscous fluid, may be positioned within the pair of cladding containment regions 54, in optical communication with the waveguide core 52. The cladding containment regions provide an effective means by which the cladding material 60 may be presented in the device 10 in a stable manner.

As is illustrated in Figs. 1-3, the extent to which buffer layer removal is effected during formation of the cladding containment regions 54 may vary. For example, in the embodiment of Fig. 1, substantially all of those portions of the buffer layer 40 aligned with the cladding containment regions 54 are removed during formation of the cladding containment region. In contrast, referring to the embodiment of Fig. 2, the buffer layer 40 is left largely unaffected by the cladding containment region forming step. In Fig. 3, substantial portions of the buffer layer 40 aligned with the cladding containment regions 54 remain, defining a remaining protective layer 42 over the electrode pattern within the cladding containment regions 54.

In the embodiments of Figs. 2 and 3, the remaining buffer layer thickness in the cladding containment regions 54 is sufficient to form an electrically insulative barrier between the pair of control electrodes 32, 34. As is illustrated in Fig. 7, if substantially all of the buffer layer thickness in the cladding containment regions 54 is removed, it may be preferable to provide an electrically insulative barrier layer 70 over the pair of control electrodes 32, 34 prior to positioning the cladding material within the pair of cladding containment regions 54. The insulative barrier layer 70 may comprise silica or any other suitable electrical insulating material.

The above description of the fabrication steps according to the present invention is general in nature because it is contemplated that a variety of suitable fabrication steps may be employed within the scope of the present invention. For example, referring to Fig. 1, by way of illustration and not limitation, it is contemplated that the waveguide core 52 may be formed through a process by which the position of the core 52 in a plane 55 offset from and generally parallel to a plane 35 occupied by the control electrodes 32, 34 is controlled relative to respective positions of the pair of control electrodes 32, 34 in the control electrode plane 35. For example, by way of illustration and not limitation, appropriate portions of the core layer 50 may be removed by patterning the core material layer utilizing a waveguide mask and, e.g., reactive ion etching the waveguide structure.

The electrode pattern 30 may comprise any suitable conductive material. It is contemplated, for example, that Au, Pt, Cr, Ta, Ti, indium tin oxide, and combinations thereof, may be suitable conductive materials. Cr is likely to be advantageous in many embodiments because of its good adhesive characteristics and relatively low resistivity. Particularly advantageous conductive materials will be characterized by melting points of at least about 1500°C. Referring to Fig. 13, it is contemplated that the electrode pattern may comprise first and second conductive layers 36, 38 - the first conductive layer 36 having relatively enhanced adhesive properties and the second conductive layer 38 having relatively enhanced conductive properties. The electrode pattern may define a thickness of between about 600 Å and about 20,000 Å.

The buffer layer 40 and cladding material 60 preferably comprise materials having refractive indices that are lower than the refractive index of the core material 50 at an operating

temperature and operating wavelength of the device. For example, where the core 52 comprises a material characterized by a refractive index of between about 1.450 and about 1.455 at a selected operating temperature and operating wavelength of the device, the buffer layer 40 and the cladding material 60 may comprise materials characterized by refractive indices of between about 1.440 and about 1.450. The buffer layer 40 and the cladding material 60 are preferably transmissive to light of at least one commonly used telecommunication wavelength, e.g, about 860nm, about 1.3μm, and about 1.55μm, or at a selected operational wavelength of the device 10.

It may be advantageous to ensure that the buffer layer 40 comprises an electrically insulating, non-metallic material. For example, the buffer layer may comprise a material selected from silica, SiOx ($1.5<x<2$), SiON, an insulating metal-oxide glass, and combinations thereof. Typical buffer layer dimensions range from between about 3μm and about 10μm in thickness, although it is contemplated that a variety of thickness dimensions will be suitable.

According to one embodiment of the present invention, the buffer layer 40 is formed through a sol-gel process characterized by a maximum processing temperature below about 400°C. In this manner, the buffer layer 40 can be formed at processing temperatures that are not likely to result in damage to or degradation of the electrode pattern 30. Sol-gel processing may be utilized to form passive, active, and nonlinear optical materials for optical devices according to the present invention. Many of the principles and desirable features of photolithographic definition can be extended to sol-gel materials. Sol-gel techniques, in which glasses are formed from organic precursors by low temperature polymerization reactions, offer attractive advantages in terms of flexibility of composition and structure. Generally, sol-gel processes consist of three steps: first, a colloidal suspension of oxide particles (the "sol") is formed by hydrolysis and condensation of a precursor (e.g. and alkoxide); next, the sol is dried such that further condensation creates a semi-rigid "gel"; finally, heat treatment of the gel is used to eliminate remaining organic ligands and to complete densification. The sol may be dip, spin, or spray-coated. Thick films can be obtained by multiple coatings.

It is contemplated that other processing schemes may be employed to form the buffer layer 40. In the event the buffer layer 40 comprises a high melting point silica-based material 21

(mp>1500°C), preferred processing schemes should be selected where buffer layer formation may be achieved at temperatures well below (e.g., at least about 500°C below) the melting point of the silica-based material 40 and the melting point of significant or major constituents of the electrode pattern 30. In this manner, buffer layers according to the present invention may be formed without causing undue damage to the materials of the electrode pattern 30. For example, in addition to the sol-gel processed described above, the buffer layer 40 may be formed through a plasma enhanced chemical vapor deposition process characterized by a maximum processing temperature below, e.g., about 1000°C.

The waveguide core material layer 50 may comprise any material suitable for operation as a waveguide core. For example, suitable materials include, but are not limited to, polymers, silica, doped silica, and combinations thereof. The waveguide core material layer 50 may be formed over the buffer layer 40 through a sol-gel process in a manner similar to that described above with reference to the buffer layer 40. The core layer 50 preferably comprises a material that is transmissive to light at 860nm, 1.3μm, 1.55μm, or any suitable telecommunication or operational wavelength of the device 10. Although a variety of core layer dimensions are contemplated by the present invention, typical core layers define a thickness of between about 3μm and about 10μm.

The cladding material 60 may comprise an electrooptic medium or any other medium where a control signal applied to the electrode pattern 30 alters the velocity, phase, polarization, amplitude, or some other transmission characteristic of light propagating along the waveguide core 52. Although a variety of conventional cladding mediums are suitable for use in the present invention, it is noted that the above-noted patent documents incorporated herein by reference include further teachings relative to selection of a suitable medium. For example, the cladding medium may comprise a polymeric or non-polymeric medium. Examples of polymeric cladding mediums include, but are not limited to, thermoplastics, thermosets, UV cured materials, cross linked materials, and sol-gel materials. The cladding material 60 may include an electrooptic chromophore and may comprise a Pockels effect medium, a Kerr effect medium, or combinations thereof. As is described in further detail below with reference to Figs. 14 and 15, the core material forming the waveguide core 52 may also comprise a medium where a control

signal applied to the electrode pattern 30 alters the velocity, phase, polarization, amplitude, or other transmission characteristic of light propagating along the waveguide core 52.

The cladding material 60 may be positioned within the cladding containment regions through a sol-gel process in a manner similar to that described above with reference to the buffer layer 40. The cladding material 60 may also be positioned within the cladding containment regions 54 as a solution, as an aerosol of a solution, as a vapor deposited material, or as an electro-deposited material. As is illustrated in Figs. 1-3, the cladding material 60 may define a thickness at least as large as a thickness defined by the core material layer 50.

Where a poled cladding material 60 is preferred, the cladding material 60 may be positioned within the cladding containment regions 54 while a poling voltage is applied across the electrode pattern 30. Preferably, the poling voltage is maintained during curing, cross-linking, drying, or thermo-setting of the cladding material. For example, where the cladding material 60 comprises an electrooptic chromophore, a poling voltage is applied so as to be sufficient to orient the chromophore along the poling field in the cladding material 60. As is illustrated in Fig. 7, the electrically insulative barrier layer 70 may be formed over the electrode pattern prior to application of the poling voltage and positioning of the cladding material 60 over the electrically insulating layer 70.

Referring now to Figs. 8-11, it is noted that an additional electrode pattern 90 may be formed on an electrode superstrate 92 of silica or other suitable material and positioned above the electrode pattern 30 formed over the electrode support surface 22 of the support wafer 20. In Fig. 8, for example the additional electrode pattern 90 comprises a single control electrode substantially aligned with the waveguide core 52. In Fig. 9, the additional electrode pattern 90 comprises a single control electrode offset along one side of the waveguide core 52 while the electrode pattern 30 formed over the electrode support surface 22 of the support wafer 20 comprises a single control electrode offset along an opposite side of the waveguide core 52. The contour of the resulting electric field is predominantly horizontal in areas relatively close to the core 52 and predominantly vertical in portions of the cladding material offset from the core 52. In this manner, the contour of the electric field is such that the respective orientations of the electric field and the poling contour are configured to compensate for optical birefringence of the

poled cladding material or optically functional core material. As a result, the TM mode index of the waveguide device 10 can be substantially equal to the TE mode index of the waveguide device 10. Alternatively, the electrodes and core may be configured such that changes in the respective indices are substantially equal. In addition, it is contemplated that the electrodes and core may be configured to affect only one of the polarization modes.

The electrode configuration of the embodiment of Figs. 10-12 are also directed at ensuring that the TM mode index of the waveguide device 10 can be substantially equal to the TE mode index of the waveguide device 10. Specifically, in Fig. 10, a single control electrode of the additional electrode pattern 90 is offset along one side of the waveguide core 52 and defines a thickness sufficient to extend alongside a substantial portion of the waveguide core 52. The control electrode of the electrode pattern 30 is offset along the opposite side of the waveguide core 52. The resulting contoured electric field is predominantly horizontal on the side of the core 52 with the enhanced thickness electrode and predominantly vertical on the opposite side of the core 52.

Similarly, in Fig. 11, one of the control electrodes of the additional electrode pattern 90 is offset along one side of the waveguide core 52 and defines a thickness sufficient to extend alongside a substantial portion of the waveguide core 52. An additional control electrode of the electrode pattern 90 is offset along the opposite side of the waveguide core 52 and defines a reduced thickness. The resulting contoured electric field is predominantly horizontal on the side of the core 52 with the enhanced thickness electrode and predominantly vertical on the opposite side of the core 52.

In Fig. 12, the additional electrode pattern 90 comprises a pair of control electrodes offset along opposite sides of the waveguide core 52. The electrode pattern 30 formed over the electrode support surface 22 of the support wafer 20 comprises a single control electrode substantially aligned with the waveguide core 52. The resulting contoured electric field is predominantly vertical in the areas of the cladding 60 aligned with the pair of control electrodes of the additional electrode pattern 90, predominantly horizontal in the areas of the cladding adjacent to the core, and predominantly vertical in the area of the core 52.

Referring to Figs. 14 and 15, the material forming the core 52 may comprise an optically functional material, i.e., an electrooptic medium or any other medium where a control signal applied to the electrode patterns 30, 90 alters the velocity, phase, polarization, amplitude, or some other transmission characteristic of light propagating along the waveguide core 52. In the embodiments of Figs. 14 and 15, portions of the buffer layer 40 are removed to define a core material containment region in which the core material is introduced. The core material containment region is defined in the buffer layer 40 prior to formation of the waveguide core 52 over the buffer layer. For the purposes of defining and describing the present invention, it is noted that the core 52 is described as being formed "over" the buffer layer 40, even though it is not positioned above the entire buffer layer 40.

In the embodiment of Fig. 14, the waveguide core material extends beyond the core material containment region to define a core material overlayer 56. In contrast, in the embodiment of Fig. 15, the waveguide core material is substantially confined within the core material containment region defined by the buffer layer 40.

Figs. 14 and 15 also illustrate two different types of electrode arrangements. It is contemplated that any of a variety of suitable electrode arrangements may be employed in the embodiments of Figs. 14 and 15, including those illustrated in the remaining embodiments of the present application.

For the purposes of defining and describing the present invention, it is noted that the wavelength of "light" or an "optical signal" is not limited to any particular wavelength or portion of the electromagnetic spectrum. Rather, "light" and "optical signals," which terms are used interchangeably throughout the present specification and are not intended to cover distinct sets of subject matter, are defined herein to cover any wavelength of electromagnetic radiation capable of propagating in an optical waveguide. For example, light or optical signals in the visible and infrared portions of the electromagnetic spectrum are both capable of propagating in an optical waveguide. An optical waveguide may comprise any suitable signal propagating structure. Examples of optical waveguides include, but are not limited to, optical fibers, slab waveguides, and thin-films used, for example, in integrated optical circuits.

For the purposes of describing and defining the present invention it is noted that the term "substantially" is utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement, or other representation. The term "substantially" is also utilized herein to represent the degree by which a quantitative representation may vary from a stated reference without resulting in a change in the basic function of the subject matter at issue.

Having described the invention in detail and by reference to specific embodiments thereof, it will be apparent that modifications and variations are possible without departing from the scope of the invention defined in the appended claims. For example, with reference to the various embodiments of the present invention, it is noted that the various core, cladding, buffer, and overlayer regions of the present invention, and different respective portions thereof, may comprise optically functional or non-functonal materials. It is also noted that waveguide devices according to the present invention may be employed in a telecommunications or other type of optical network. In addition, although some aspects of the present invention are identified herein as preferred, typical, or particularly advantageous, it is contemplated that the present invention is not necessarily limited to these aspects of the invention.

What is claimed is: